Change in Vibrato Rate and Extent During Tertiary Training in Classical Singing Students

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Summary: Objectives. Vibrato is an integral and desirable feature of the classical singing voice. For elite singing students, achieving and developing vibrato may constitute one of the essential elements of their vocal training, although it is not necessarily a focus of that training.

Study Design. In this longitudinal study, we measured vibrato rate (VR) and vibrato extent (VE) and regularity (SD) of VR and VE in student singers over the course of four semesters of tertiary level voice training at a conservatorium of music to determine how these parameters changed during training.

Method. Fifteen singers completed four semesters (2 years) of training. Singers performed four sustained pitches across their vocal range. Peaks and troughs of vibrato were isolated from the fundamental frequency trace to calculate VR in hertz and VE in semitones.

Results. Analysis using linear mixed models revealed significant increases in VE and decreases in VRSD over time. VR was within expected limits for classical singers in all semesters, and small VR reductions were not statistically significant between semesters over 2 years of training. VE showed significant increases between the start of year 1 and year 2. Periodicity of singers' VR (SD) improved over training, with significant decreases to VRSD over time. There was no significant change to VESD.

Conclusions. Future studies will ascertain whether further changes to VR and VE occur over longer training periods, or whether the major changes occur early in tertiary training.

Key Words: Singing training–Vibrato rate–Vibrato extent.

INTRODUCTION

Vibrato, the constant modulation of fundamental frequency ($F0$), is considered a consequence of good singing[1] and a desirable component of overall tone quality.[2] Although singers and pedagogues may not focus directly on their vibrato during classical singing training, it provides a key perceptual indicator of technical and artistic accomplishment.[3–6] The sound quality of a successful vibrato has been difficult to verbalize and has been expressed using both functional and timbral terms such as vocal coordination,[4] richness,[7] and vibrancy.[6] Conversely, inconsistent or uneven vibrato is indicative of poor or faulty vocal technique[4,6] and inferior sound quality. A classical voice without vibrato has been described as "dull" or "spread" and lacking in ring,[4] freedom, and power.[6] To the elite singer in training, achieving an even and appropriate vibrato may constitute one of the essential elements in vocal development.[6]

Vibrato is quantifiable by rate (the number of cycles per second [hertz]), extent (fluctuation of pitch above and below the mean pitch), and onset (delay from onset of phonation until the first vibrato cycle)[8] of the $F0$ modulations. In vibrato tones, these $F0$ modulations are accompanied by amplitude modulations, or variations of loudness and timbre,[5] because the varying $F0$ affects the prominence of amplitudes of spectral partials as $F0$ modulates.[9] Frequency modulations are considered most relevant to the perception of vibrato.[10] A number of studies have identified superior vibrato quality in terms of regularity and consistency,[11–14] and a near sinusoidal $F0$ pattern.[15]

Vibrato rate (VR) has been found to vary between 4.1[16] and 6.7 Hz[11] with a mean rate of 6 Hz in professional singers. The vibrato of advanced students embarking on professional careers ranged from 5.23 to 7.27 Hz.[3] Vibrato extent (VE) has been widely associated with classical and operatic singing.[12] In studies of professional singers, VE varied above and below the mean $F0$ by an average of 5–7% of $F0$,[12,17] or by 0.5–2 ST,[18] but VE could vary between 1% and 14% depending on stylistic demands of the repertoire and other factors.[19] In advanced female singing students at the completion of 5 or more years of professional training, VE ranged from 1 to 1.63 ST.[3] Wider VE has been considered characteristic of operatic singing more than concert or early music singing and professional singers have altered VE for the stylistic requirements of particular genres (eg, opera vs concert songs, sung by the same singers).[20,21] There is also evidence to suggest that professional singers communicating emotion increase their VE at points of high drama.[17,22,23] Few studies have addressed habitual VE or depth of vibrato as a result of vocal technique or training.[3]

The individual singer's vibrato is the most consistent feature of vocal quality in professional classical singing.[10,24,25] In student singers, vibrato develops spontaneously as singing voices mature.[8] Perceptual and acoustic studies have assessed the degree to which student singers demonstrate an "appropriate vibrato,"[1,26] but few studies have associated particular training techniques with appropriate vibrato. Mitchell and colleagues[3,27,28] investigated the application of one specific pedagogical technique; that of "open throat" (OT), which is widely regarded as fundamental to good singing quality. The instruction to achieve a "warm" or "free" sound was achieved by the use of vocal gestures such as "sob," "laugh," or "maintaining the posture of inhalation." When singers were instructed to

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use a reduced OT rather than maximal OT, analyses revealed significant reductions in VE and increases in onset time, but no change to VR. Applying a singing technique made a significant difference to the overall sound quality and expert listeners were able to perceptually identify, with a high degree of accuracy, the presence of OT in the vocal quality.

Research on the effects of advanced vocal training on vibrato has produced mixed results. Singing students undertaking advanced voice training averaged VR of 5.5 Hz in two separate studies and this VR remained constant both before and after years of tertiary training.[13,14] VR was found to be the most stable and consistent element of vocal vibrato over time. Mendes et al[14] showed no difference in VR or VR regularity in groups of young, mostly female, singers in training, whereas Mürbe et al[13] reported that singers' VR consistency (measured as standard deviations [SDs]) at mezzo forte (mf) reduced from 0.49 to 0.39 Hz between the start and the completion of their 3-year training program. Further, they noted that vocal training in young singers consolidated VR variations and reduced VR in singers who were at the extremes of the VR range but did not report on the changes that may have occurred during stages of tertiary training. Mendes et al[14] also examined amplitude variations in singing students' vibrato and reported low values (in comparison to professional singers), which did not vary during the course of vocal training. Neither study on student singers[13,14] focused on the impact of training on VE.

For individual professional singers, the regularity of vibrato cycles may change[11] within a single note, although such variations (or SDs) in mean VR are insignificant.[13,14] Across the pitch range, there have been no consistent differences reported, either in VR or VE, between singers' production of different *F*0s.[16,29] Loudness or differences in sound pressure level (SPL) have been associated with changes in vibrato parameters[30,31] and equally, made no significant difference to VR in soft and loud singing.[13,16] VE can be influenced by SPL, but the effect does not demonstrate a consistent difference throughout SPL range.[30,32]

Using the *messa di voce*, a crescendo-diminuendo on a single note, and a pedagogic tool for accomplishing and maintaining uniform timbre,[6] we assessed singers' VR and VE over the first 2 years of tertiary study to identify any systematic changes that occurred in these parameters. In addition, we assessed the effects of different dynamic levels within the *messa di voce* in the acquisition of vibrato.

METHOD

Ethics

The institutional human ethics committee from the University of Sydney approved the study.

Participants

Twenty-eight singers volunteered to participate in a longitudinal study of singing. They were the first-year cohort of voice students at a leading conservatorium of music in Australia and had been accepted into the degrees of Bachelor of Music as voice majors (n = 12), voice minors (n = 8), or into the Diploma of Opera (n = 6). Fifteen singers completed four semesters (2 years) of training.

Singer protocol

Singers performed four *messe di voce* (MDV) across a triad plus the octave starting on a pitch appropriate to their voice type (soprano: G4, mezzo: D4, tenor: E3, baritone: C3). Singers sang on one occasion each semester (ie, half year) for 2 years (ie, four times).

Recording

Singers were recorded in a studio lined with sound absorptive curtains (www.jands.com.au) to suppress first-order room reflections. The resulting dead space was appropriate for recording voices for acoustic measurement but more comfortable for singers than an anechoic chamber.

The acoustic signal was captured using a measurement-grade microphone (Brüel & Kjær 4939, Bruel & Kjaer Sound and Vibration Measurement, Naerum, Denmark) positioned on a head boom at a constant 7 cm distance from the singer's lips. This close microphone tracks singer movements, and further eliminates most room acoustics effects.[33] The level was adjusted *via* a Millenia pre amplifier with stepped controls (HV 3D-8 Microphone Preamplifier, Millenia Music Media Systems, Placerville, CA). The audio channel was digitized (Apogee AD-16X analogue to digital converter, Apogee Electronics Corp., Santa Monica, CA) and transferred to computer (Carillon AC-1/HD+ Computer with RME AES16 sound card, Haimhausen, Germany *via* AES digital standard cable) and saved in an *Adobe Audition* session (24 bit, 48 kHz wave files). Recordings were calibrated (Brüel & Kjær DP 0887, Naerum, Denmark) so the singer's absolute sound pressure was known at these microphones.

Acoustic analysis

Audio files were edited in *Adobe Audition* (Version 1.5, Adobe Systems Inc., San Jose, CA). Acoustic analysis was automated in *Praat*[34] and *Microsoft Excel*, Microsoft Corp., Redmond, WA. *F*0 and SPL were calculated at 100-ms intervals and results exported to an excel spreadsheet. The midpoint of the MDV was identified from the SPL trace. In Excel, peaks and troughs of vibrato were isolated from the *F*0 trace to calculate rate in hertz and extent in semitones.[3] Finally, files were checked manually and if no sinusoidal vibrato was evident or the trace revealed an irregular frequency modulation, a nil result was recorded. Ten cycles around the maximum SPL point of each MDV were used to calculate mean and SD VR and VE for each singer. In addition, a further three points were used to compare soft and loud portions of the MDV. Three vibrato cycles from the onset (pp start), midpoint (ff mid), and end (pp end) of each MDV were calculated to compare the effect of the dynamic range on singers' vibrato. Singers' VR and VE were averaged over the four pitches at each time recording to create one value per semester.

Statistical analysis

Mean values and SDs were used to describe VR and VE averages and SDs at each semester time. Linear mixed models were used to measure the independent effects of each MDV measured at the same time and then to assess whether there were differences between each MDV over time within subjects. This method was chosen as the first line of analysis because of missing data in the sample set where singers did not produce a measurable vibrato on every note. A compound symmetry covariance matrix provided the best fit, that is, an Akaike's Information Criterion value for the models used for time comparisons than either a diagonal, unstructured, or autoregressive matrix and was therefore used in these mixed models. A compound symmetry matrix specifies that the measurements equal variance over time and that all pairs of measurements from the same person have the same correlation, that is, there is constant variation and covariance. This structure makes no assumptions about equal spacing between time points and is equivalent to repeated-measure analysis of variance.

TABLE 1.
Participants' Vocal Characteristics by Gender, Group (Opera, Major, Minor), and Voice Type

		Females		Males	
	Opera	Major	Minor	Major	Minor
Soprano	2	4	2	—	—
Mezzo	—	1	2	—	—
Tenor	—	—	—	1	1
Baritone	—	—	—	2	—
Total	2	5	4	3	1
Average age* (y)	22.7	18.4	20.8	21.5	17.5
(SD)*	(0.8)	(0.3)	(3.9)	(2.4)	—

* Average age and SDs at commencement of degree.

RESULTS

Fifteen singers completed four semesters of singing training (group demographic indicated in brackets in Table 1). Of the 15 singers, 11 were female and four were male. There were eight sopranos, three mezzo-sopranos, two tenors, and two baritones. Two were studying for a Diploma of Opera and eight were enrolled as majors and five as minors in the Bachelor of Music degree. The demographic information of the participants is presented in Table 1.

Vibrato measures, VR and VE, are presented in Table 2, showing the estimated marginal means from averaging all singers' vibrato parameters in each semester, for VR and VE and SDs in the production of VR and VE. The mean VR across all subjects was 5.38 Hz in semester 1 and decreased to 5.21 Hz by semester 4. VE increased from 0.37 in semester 1 to 0.48 ST by semester 4, averaged across all singers. VR periodicity tended to decline from 0.51 to 0.34 Hz by semester 4, whereas VE consistency was unchanged (0.1 ST). Differences in VR, VE, and SDs were considered by semester for the effects of training and development.

VR and VE were tested for time differences between semesters. Table 3 shows the between-time differences in the marginal mean values for each VE as computed using mixed models. Where the *P* values for VE average differences are statistically significant, they represent a significant increase over time as shown by the negative sign of the mean difference. Mean VE values increased over four semesters and there are three statistically significant differences showing an increase in VE from semester 1 to semesters 3 and 4 and between semesters 2 and 4. There was no statistically significant difference in VR values between any pair of semesters.

VRSD and VESD values were also tested for time difference. VRSD decreased over four semesters (Table 4). There were statistically significant differences demonstrating a decrease in VRSD between semesters 1 and 3–4 and which was between the start of year 1 and year 2. There were no statistically significant differences in SD values for VE in four semesters of training.

Figure 1 shows VR and VE in semester 1 compared with semesters 2, 3, and 4 for individual singers who successfully produced vibrato measures in each of the four semesters. In each figure, the distribution of data points around the diagonal midline indicates the direction of these differences in semesters 2–4 in comparison with semester 1. Singers' VR was relatively constant across all semesters and decreased slightly in subsequent semesters, particularly in semester 4. For most singers, VE increased after semester 1 and most VE comparisons show these increases after semester 4. Three females (one major, two minors) in this group did not demonstrate a regular sinusoidal vibrato in all MDV productions. Of this group, one minor developed a regular vibrato in the second semester and one major and one minor did not develop a sinusoidal vibrato pattern on all notes during the 2 years of the study.

The effect of dynamic range on VR and VE

Figure 2 shows VR and VE differences by dynamic (pp start, ff mid, and pp end) in each semester (1–4). Not all singers

TABLE 2.
Estimated Marginal Means With Standard Errors in Brackets for Average VR, VE, and SDs of Rate (VRSD) and Extent (VESD) for Each Semester

Semester	VR (Hz) (SE)	VRSD (SE)	VE (ST) (SE)	VESD (SE)
1	5.38 (0.12)	0.51 (0.05)	0.37 (0.04)	0.10 (0.01)
2	5.27 (0.12)	0.46 (0.05)	0.38 (0.04)	0.09 (0.01)
3	5.24 (0.12)	0.36 (0.05)	0.43 (0.04)	0.10 (0.01)
4	5.21 (0.12)	0.34 (0.05)	0.48 (0.04)	0.11 (0.01)

TABLE 3.
Pairwise Comparisons of Marginal Means of VE Averages From Mixed Models to Estimate Between Time (Semester) Differences

Time Contrast	Fixed Effects, *P* Value for Time for VE Average	Mean VE Average Difference	95% Confidence Intervals		Time Contrast, *P* Value*
			Lower	Upper	
1 vs 2	0.005	−0.015	−0.102	0.073	1.000
1 vs 3		−0.065	−0.153	0.023	0.276
1 vs 4		−0.109*	−0.196	−0.021	0.009
2 vs 3		−0.050	−0.136	0.036	0.676
2 vs 4		−0.094*	−0.180	−0.008	0.026
3 vs 4		−0.044	−0.130	0.042	0.989

Adjustment for multiple comparisons: Bonferroni.
* $p < .05$.

produced a measurable vibrato at each dynamic point. The distribution of data points around each plot's diagonal midline indicates the similarity between the different dynamic points in the MDV each semester. VR and VE were consistent between the dynamic points pp start-ff mid. In Figure 2A, VR points are closely spread regardless of semester. Figure 2B shows a greater number of data points above the diagonal midline, suggesting a slight increase in VE during ff mid in comparison to pp start, but this was not consistent by semester.

Individual differences in VR and VE

Singers showed idiosyncratic vibrato patterns and interaction between VR and VE. Figure 3 presents exemplars of overall VR/VE relationships at the ff mid for four female singers and three male singers in semesters 1–4. Data points are grouped by singer to indicate the similarities and differences during the training period. VE is plotted against VR for the four semesters and each singer's data points are circled.

In the female exemplars (Figure 3), there are two majors, one minor and one soprano who successfully transferred from minor to major. For all singers, VR is focused around 5 Hz but VE varied across singers. One major female showed very little change from semesters 1 to 4, whereas the other increased VE by over 0.25 ST. The minor to major female showed a large VE across the four semesters. The minor female did not demonstrate vibrato in semester 1 and showed variable VR and VE in semesters 2–4.

For males, Figure 3 presents the highest ranked and mid ranked majors and one minor (based on audition scores). The highest ranked major showed the slowest VR in all semesters and the mid ranked major showed the greatest variation in VR over the four semesters. By semester 4, they demonstrated similar VE, but VR varied by over 1 Hz between singers and the highest ranked singers showed VR below 5 Hz by semester 4.

DISCUSSION

After 2 years' tertiary vocal training, singers demonstrated an increase in VE and a slight decrease in VR. VE increases were significant between year 1 (semester 1 or 2) and the end of year 2 (semester 4), whereas the decreases in VR were not statistically significant between pairs of semesters. Singers' VR periodicity (measured as SD) also improved significantly from the start of year 1 to year 2 but VE was consistent between cycles throughout training. Vibrato parameters were highly individualistic, but most singers showed the same patterns in their vibrato development over time, where there was an increase in VE and a stabilization of VR consistency (VRSD).

Overall, mean vibrato VR were fractionally lower than the 5.5 Hz average reported in previous longitudinal studies of

TABLE 4.
Pairwise Comparisons of Marginal Means of VRSD Averages From Mixed Models to Estimate Between Time (Semester) Differences

Time Contrast	Fixed Effects, *P* Value for Time for VRSD Average	Mean VRSD Average Difference	95% Confidence Intervals		Time Contrast, *P* Value*
			Lower	Upper	
1 vs 2	0.004	0.043	−0.091	0.178	1.000
1 vs 3		0.142*	0.008	0.277	0.033
1 vs 4		0.167*	0.033	0.302	0.008
2 vs 3		0.099	−0.034	0.232	0.268
2 vs 4		0.124	−0.009	0.257	0.081
3 vs 4		0.025	−0.108	0.158	1.000

Adjustment for multiple comparisons: Bonferroni.
* $p < .05$.

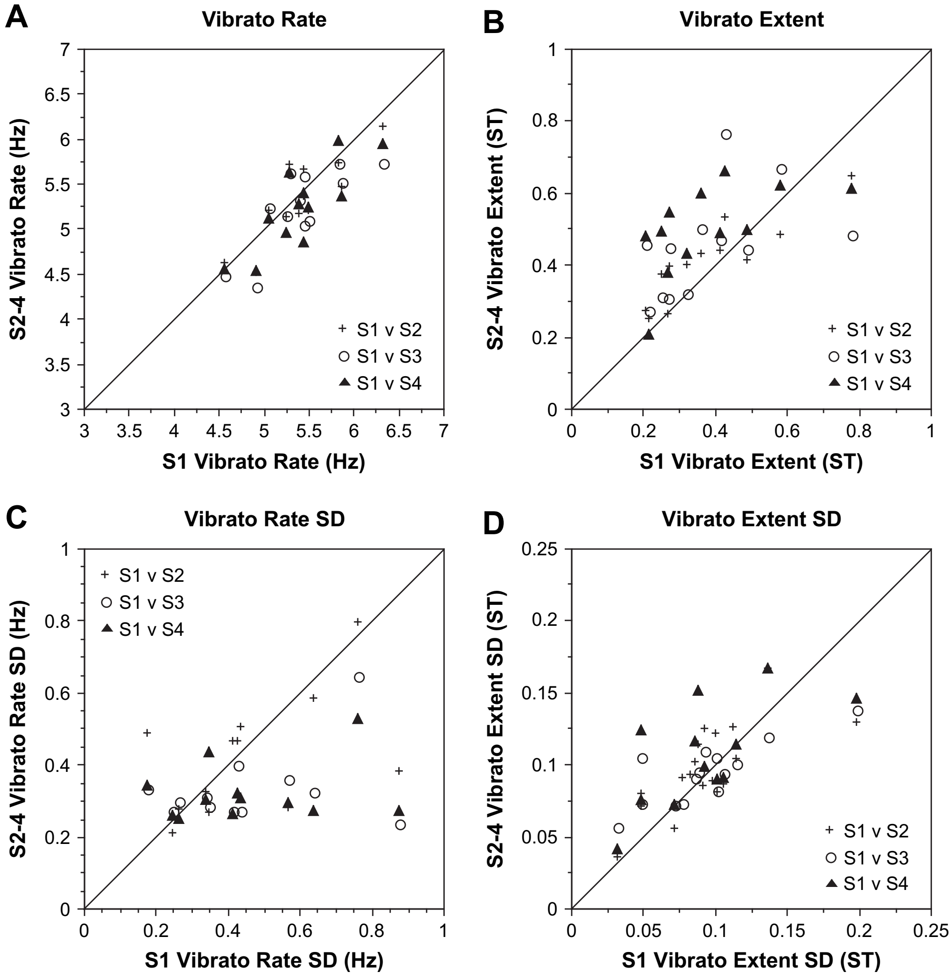

FIGURE 1. Comparison of 12 singers' mean vibrato rate (VR) and vibrato extent (VE) and SDs. **A.** VR. **B.** VE. **C.** VRSDs. **D.** VESDs. Semester 1 is plotted on the *x*-axis and semesters 2, 3, and 4 are plotted against semester 1 on the *y*-axis.

students' vibrato[13,14] and lower than the 6 Hz in studies of professional singers.[35] For these singers, VR reduced by an average 0.17 Hz between the start and completion of 2 years' training. The pattern of average VR decreases during the training period (Table 2) did not reach statistical significance but did show a reduction between semesters 1 and 4. These findings confirm other studies of singers in training, which have found VR to be the most stable and consistent element of vocal vibrato over time.[13,14] Singers in this study were younger than those in Mürbe et al,[13] commencing their degrees at on average, at 20.2 years but singers demonstrated the same consistency in their production of VR over time. Age has been associated with vibrato change in older singers toward the end of their careers[16,36] but studies have not assessed vibrato of younger voices undertaking tertiary singing training.

Periodicity or regularity of VR (measured as SD) improved during training, whereas VE maintained an evenness or regularity, which was not affected by semester. VR SD values, which represent vibrato regularity, were reduced from semesters 1 to 4 (from 0.51 to 0.34 Hz). The differences were statistically significant between semester 1 of year 1 and year 2, but not between semesters in the same year. From these SD results, we might infer that there was a tendency for singers' VR to be more consistent within a single note after four semesters' training. Results here accord well with Mürbe et al's[13] data from singers undertaking tertiary training, where vibrato SD reduced from 0.49 to 0.39 Hz but did not replicate such high VRSDs for individual singers either before or after training.

VE significantly increased by 0.11 ST from 0.37 to 0.48 ST following training. For this group of singers, there was an effect of training time on VE between year 1 and semester 2 of year 2. VE has been associated with singing quality and good technique, whereas reductions in VE, compared to optimal production, have been considered a technical flaw.[3] In this study, singers' VE consistency (VESD) did not change over time and VESD, to a greater extent than VRSD, remained more constant during training and could be considered a reliable representation of singers' habitual vibrato parameters at any semester time point.

Vibrato parameters VR and VE have been susceptible to different SPL levels,[19] and indeed as a result of the crescendo or MDV.[30,31] It was therefore important to examine the consistency of singers' vibrato production between different dynamic ranges. We compared three vibrato cycles at the start, midpoint, and end (pp-ff-pp) of each MDV to identify any effect of these SPL points

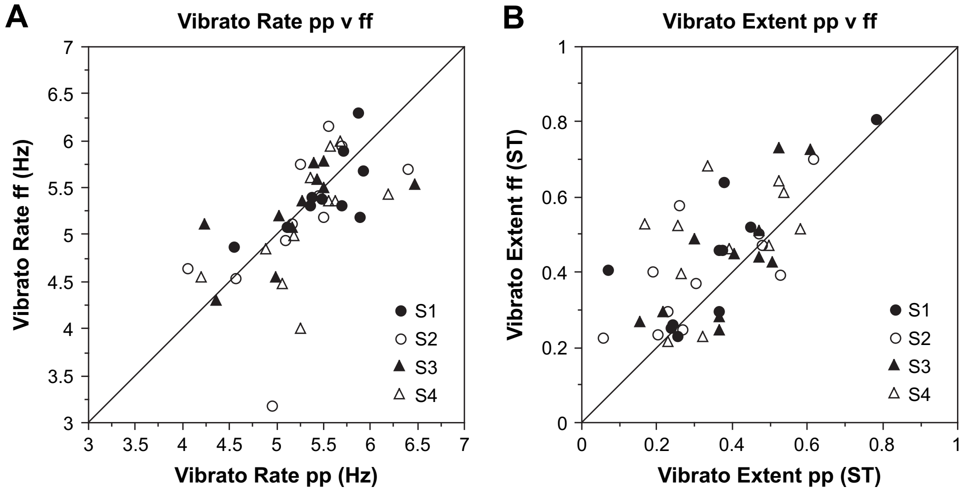

FIGURE 2. Vibrato rate (VR) and vibrato extent (VE) comparisons by dynamic portion of the messa di voce. **A.** VR at pp start and ff mid. **B.** VE at pp start and ff mid.

on singers' vibrato. Not all singers produced a viable vibrato pattern at the start and end (pp) of the MDV. Where vibrato was evident, a visual inspection of VR and VE comparisons (Figure 2) identified a slight increase in VE from pp to ff, but not in all semesters or for all singers. Singers did not demonstrate any systematic differences over time or between semesters. These results match Mürbe et al's[13] comparisons of VR at dynamic levels mp and mf where there was no statistical effect as a result of different dynamic levels. Although Figure 3B showed a proliferation of higher VE during ff mid, we did not conclusively identify an increase in VE by all singers at the mid of the MDV as identified in professional singers[31] by comparing singers pp start to ff mid.

Vibrato parameters VR and VE were highly idiosyncratic, yet these singers' VR was not outside acceptable parameters for classical singing. The results obtained from this sample of singers were within the expected range for professional singers, as the voice has a natural tendency to oscillate within a 5–6 Hz range. Figure 3 presents exemplars from male and female singers that show large inter- and intrasubject differences in vibrato parameters. Males' VR showed greater variability between singers than females' VR. This type of intersinger difference, of up to 1 Hz is not unexpected and confirms previous data on individual singers' VR.[3] Despite acoustic, physiological, and perceptual studies, it is difficult to reach consensus on what constitutes ideal vibrato and how this alters during professional singing training[13,14] and indeed, when vibrato develops in advanced singing students. For example, an absence of vibrato in advanced singing students has been associated with poor technique[3] but it has not been investigated as a feature of singers who are accepted to advanced vocal training.

A methodological strength of this study was the repeated observation of singers in advanced training. Although other studies have measured differences in singing at the start and end of training, we were able to identify key stages in singers' vibrato accomplishment. Specifically, we observed the increase of VE, between year 1 (semesters 1 and 2) and the end of year 2 (semester 4). This study was able to correlate more precise stages of development during training with changes to measurable features of voice. Figure 3 suggests that females demonstrated a greater homogeny in VR than males (Figure 3) at

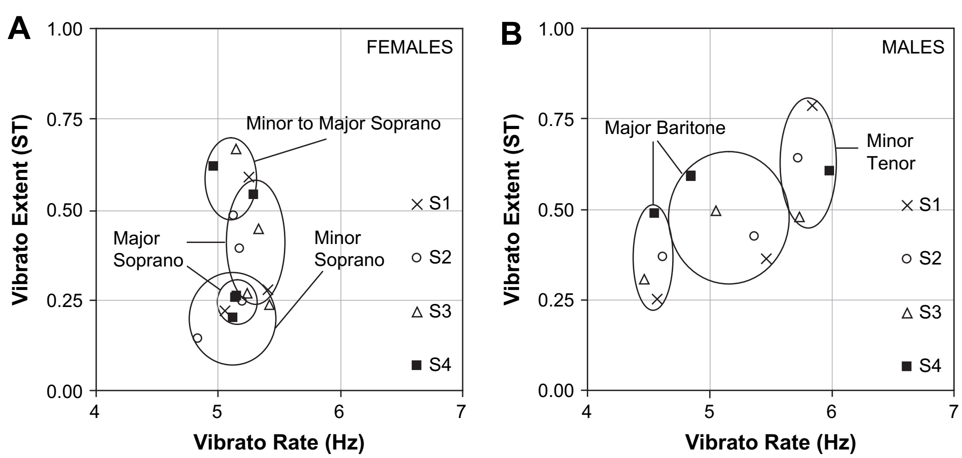

FIGURE 3. Exemplars of individual females (**A**) and males' (**B**) VR and VE means in each semester. Each singer's four semester data points are circled. Arrows indicate the group designation (major or minor) and voice type of each singer.

any given semester and across all semesters, regardless of group designation (major/minor). Two major sopranos demonstrated notably wider VE than the other two sopranos and interestingly, the soprano with the widest VE successfully transferred from minor to major at the end of semester 2. The changes to vibrato parameters could not be exclusively linked to group designations (major/minor) in these exemplars for males or females.

In this study, we focused on $F0$ modulations of vibrato and did not relate these to variations in intensity or amplitude vibrato. It may be that increased extent of the $F0$ vibrato modulations also results in an increase of the extent of the amplitude vibrato. This is worthy of further exploration to determine the development of optimal vibrato quality in advanced singing students, particularly as other studies of singing students in training discovered no changes to intensity vibrato over time.[14] There are many possible relationships between frequency and amplitude vibrato, which may be exclusive to individual singers and variable by pitch. Future perceptual studies in this longitudinal project will first examine expert listeners' responses to these singers' performances to see if there are perceptible differences in vocal quality, which reliably differentiate between key stages of training as identified in this study and if a wider vibrato is associated with improvements to vocal quality.

Assessment of this cohort of singers in training found systematic longitudinal differences in vibrato parameters between semesters 1 and 4 of tertiary vocal training. VR decreased slightly over time and VE tended to increase over time, and these differences were statistically significant. VR consistency (VRSD) improved over time, whereas VE consistency remained the same regardless of semester. Intrasinger VR and VE were highly variable and particular to singer and these results demonstrated the complex nature of defining successful vibrato parameters for individual singers and also as a result of training. Because changes were more noticeable between semesters 1 and 4, it is possible that any consistent change or improvement in vocal quality as assessed by VR and VE may not be evident until after more than 2 years of intensive instruction. A further follow-up study will assess these students' VR and VE at the end of their 3-year degree and may discover more consistent and interpretable findings as a result of training.

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